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Food, Energy and Environment: is Bioenergy the Missing Link?

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Food, Energy and Environment: Is Bioenergy the Missing Link?[1]

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The present paper studies price linkages between the food, energy and bioenergy markets. We develop a vertically integrated multi-input, multi-output market model with two price transmission channels: a direct biofuel channel and an indirect input channel. We test the theoretical hypothesis by applying time-series analytical mechanisms to nine major traded agricultural commodity prices, including corn, wheat, rice, sugar, soybeans, cotton, banana, sorghum and tea, along with one weighted average world crude oil price. The data consists of 939 weekly observations from January 1993 to December 2010. The empirical findings confirm the theoretical hypothesis that the prices for crude oil and agricultural commodities are interdependent. Commodities not directly used in bioenergy production are also included in the analysis: a USD 1/barrel increase in oil prices and agricultural commodity prices increase by between USD 0.09/tonne and USD 1.65/tonne. Contrary to the theoretical predictions, the indirect input price transmission channel is found to be small and statistically insignificant.

Keywords: Energy, bioenergy, crude oil, prices, food, renewable fuels, cointegration.

JEL classification: C14, C22, C51, Q11, Q13, Q42.

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1 Introduction

The potential role of bioenergy in the recent food price increase has sparked lively debate and controversy concerning the contribution of biofuels to food commodity price developments. On the one hand, international organisations, such as the World Bank, the FAO, and the OECD, argue that biofuels were an important factor leading to higher food prices (Mitchell, 2008; FAO, 2008; OECD, 2009). On the other hand, the EU and US policy executives play down the importance of biofuels in the recent food price developments. For example, the USDA agrees that the biomass demand for biofuels has an impact on food commodity prices, but argues that it is not a major factor (Reuters, 2008). Similarly, the European Commission acknowledges that energy prices affect food commodity prices through the indirect input channel by increasing the cost of inputs, such as nitrogen fertilisers and transport costs. However, the European Commission argues that the impact of biofuels is rather small (European Commission, 2008).

Price volatility has similarly increased in energy and agricultural commodity markets, which raises the question about the links between fossil energy and agricultural commodity prices. Three types of approaches have been followed in the literature. First, cointegration analyses are performed to estimate the long-run relationship between fuel and biomass prices (Campiche et al., 2007; Yu et al., 2006; Hameed and Arshad, 2008; Imai et al., 2008). The main shortcomings of these reduced-form empirical studies are that they do not provide a theoretical basis about the relationship, and they do not identify price transmission channels. Secondly, theoretical models are developed to identify and understand the channels of adjustment between agricultural, bioenergy and energy markets (Gardner, 2007; de Gorter and Just, 2008, 2009, Saitone et al., 2008). This strand of literature is relatively new and only few theoretical models exist to date. Thirdly, partial and general equilibrium (CGE) models have been developed to simulate the interdependencies between agricultural, bioenergy and energy markets (Arndt et al., 2008; Hayes et al., 2009; Birur et al., 2008; Tokgoz, 2009). The main disadvantage of the CGE approach is that the simulated effects largely depend on calibrated or arbitrary assumed price transmission elasticities. No study to date combines theoretical underpinnings with empirical evidence in a unified framework, which is the main purpose of this paper.

The objective of this paper is to theoretically and empirically examine the interdependencies between the energy, bioenergy and agricultural markets. Our theoretical model (section 2) builds on the models developed by Gardner (2007) and de Gorter and Just (2008, 2009), which develop a vertical market integration model of ethanol, by-product and corn markets. Our study contributes to the literature by including the indirect input channel of price transmission between food and biofuel prices in the model. Our second contribution is to analyse price transmission not only for agricultural commodities directly used but also for those commodities not employed in biofuel production. The theoretical model's results are verified in a simulation analysis.

Our empirical approach (section 3) is based on cointegration analysis (Johansen, 1988; Johansen and Juselius, 1990). We examine the long-run relationship between crude oil and agricultural commodity prices by estimating an error correction model. We firstly tested the ten price series for stationarity using the Augmented Dickey-Fuller and Phillips Perron tests. Based on the unit root test results we tested for cointegrating vectors among the nine agricultural commodity price series and crude oil price. Finally, in order to identify a structural model and determine whether the estimated model is reasonable, we performed innovation accounting and causality tests on the estimated error-correction model.

In line with theoretical predictions, our empirical estimates show that the transmission between the oil price and the agricultural commodity prices mainly occurs through the biofuel channel. Contrary to theoretical predictions, the empirical analysis suggests that the price transmission for the indirect input channel is small and statistically insignificant. The Granger causality test results suggest a long-run unidirectional causality from the oil price to agricultural commodity prices. However, the tests deny the presence of a similar relation in the opposite direction.

2 Theoretical framework

2.1 Bioenergy models in the literature

Several models have been developed for studying the effect of biofuels on agricultural markets. Gardner (2007) developed a vertical market integration model of ethanol, by-product and corn markets to analyse the effects that corn and ethanol subsidies have on welfare in the US. The main shortcoming of this model is that the ethanol market is modelled separately from the aggregate fuel market (fossil fuel and biofuels). The price transmission between fuel and corn depends crucially on the assumption about the cross-price elasticity between fuel and ethanol.

De Gorter and Just (2008, 2009) extended the Gardner's model by incorporating ethanol in the aggregate fuel market. The price transmission between fuel and corn is effectuated through the demand for corn in ethanol production and occurs when the fuel price is high enough and/or when the corn price is low enough, ensuring that corn-based ethanol production is more profitable than corn for food use.[4] Saitone et al, (2008) also focused on the US ethanol/corn sectors and income distribution effects of ethanol subsidies. They showed that market power upstream in the input market and downstream in the corn-processing sector may constrain price transmission between ethanol and corn.

Although innovative, these models contain important methodological shortcomings. In particular they fail to account for some key inter-linkages present in the fuel-biofuel-food markets. First, all three models described above show that the price transmission from fuel to agricultural markets is effectuated only through the demand for agricultural commodities in biofuel production. They do not consider the indirect input channel. In reality, fuel is an important input in agricultural production, such as diesel, fertilisers and pesticides; hence it affects agricultural prices through the agricultural

[4] Price transmission will not occur for low fuel and/or high corn prices. In this case, the corn-based ethanol production is not competitive, implying zero ethanol production in equilibrium.

production costs. Ignoring this effect may lead to upward bias in estimates of biofuel expansion on agricultural prices. Second, all three models only consider one agricultural commodity (i.e. that used for biofuel production). With multiple commodities, the derived effects may change and the fuel market may affect not only biomass crops, but also those commodities, which are not directly used in biofuel production.

2.2 The model

The present study builds on models developed by Gardner (2007) and of de Gorter and Just (2008, 2009) and introduces two important extensions. First, to account for cross-commodity price effects, we introduced two agricultural commodities: one suitable for biofuel production (referred to as 'biomass')[5] and one not suitable for biofuel production (referred to as 'food'). Second, we consider the price transmission also through the input channel by explicitly modelling the agricultural input markets. Furthermore, to take into account the international price linkages, we have not focussed on a particular region but the model is for the world market in general.

The world economy is assumed to consist of vertically integrated agricultural, biofuel, fossil fuel, by-product, and input markets. We assume that the representative farm can substitute between producing two agricultural commodities (biomass and food) using constant returns to scale production functions of two substitutable inputs: fuel and other inputs (referred to as 'land'). Biomass output can be supplied to both food and biofuel markets whereas food commodity can only be supplied to the food market. The biofuel sector uses biomass to produce biofuels and by-product. The aggregate fuel market is a sum of biofuel and fossil fuel.

We firstly considered the agricultural sector. The representative agricultural farm is assumed to maximise a standard profit function which is the difference between sales revenue from biomass and food commodity and cost expenditures on land and fuel: $\Pi = \sum_i p^i Q^i(N^i, K^i) - wN^i - rK^i$ (for $i = AB, AN$), implying the following equilibrium conditions:

$$p^i \partial Q^i / \partial N^i = w \qquad \text{for } i = AB, AN \qquad (1)$$

$$p^i \partial Q^i / \partial K^i = r \qquad \text{for } i = AB, AN \qquad (2)$$

where Q is production function, N is non-fuel input (land), K is fuel input, p is farm output price, w is land rental price, and r is fuel price. The indexes AB and AN stand for biomass and food commodity, respectively. Equations (1) and (2) describe the marginal conditions for land and fuel inputs, respectively. Solving equations (1) and (2) yields farm input demand and output supply of agricultural commodities as a function of output and input prices.

We then considered biofuel production. We assumed a constant Leontief transformation technology in the biofuel sector with the constant extraction coefficient denoted by β. Each biomass unit results

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[5]Note that we have considered the case where the agricultural commodity suitable for biofuel production may be used for both food and biofuel production. We have named it biomass to simplify the text.

in β units of biofuel.[6] Additionally, biofuel production yields feed by-product, γ, measured in terms of feed quantity per unit of biomass. To simplify the analyses, we assumed constant value of unit processing costs (adjusted for the mark-up), c, incurred to biofuel production from one unit of biomass. Therefore, biofuel profitability is determined by both biomass and by-product prices net of processing costs. The possibility to use biomass for both food and biofuel productions implies that biofuel, $S^B(r)$, and by-product, $S^O(p^O)$, supplies represent the excess supply of biomass over biomass food demand adjusted by the extraction coefficients, $S^B = \beta\left(S^{AB} - D^{AB}\right)$ and $S^O = \gamma\left(S^{AB} - D^{AB}\right)$, respectively, where p^O is the price for by-product.

The world's fossil fuel supply together with the biofuel supply generate the aggregate fuel supply curve, $S^{TF}(r) = S^F + S^B$, where $S^F(r)$ is the world supply curve of fossil fuel. The aggregate fuel demand, $D^{TF}(r)$, is a sum of agricultural fuel demand, $K^{AB} + K^{NB}$, and non-agricultural fuel demand, $D^{NF}(r,t)$, where t is an exogenous parameter, which we used to derive the comparative static effects of fuel demand shocks.[7]

The market equilibrium conditions can be summarised as follows:

$$\text{if} \quad p_o^{AB} \geq \beta r + \gamma p_o^O - c \quad \Rightarrow \quad S^B = S^O = 0 \quad \Rightarrow \quad D^{AB} = S^{AB} \tag{3a}$$

$$\text{if} \quad p_o^{AB} < \beta r + \gamma p_o^O - c \quad \Rightarrow \quad S^B > 0, S^O > 0 \quad \Rightarrow \quad S^{AB} - D^{AB} > 0 \; \Rightarrow p^{AB} = \beta r + \gamma p^O - c \tag{3b}$$

$$S^{AN} = D^{AN} \tag{4}$$

$$N^{AB} + N^{AN} = S^N \tag{5}$$

$$S^O = D^O \tag{6}$$

$$S^{TF} = D^{TF} \tag{7}$$

where p_o^{AB} is equilibrium price of biomass in the absence of biofuel production, p_o^O is by-product price in the absence of production of by-product from biomass, $S^N(w)$ is world supply of land, $D^O(p^O)$ is by-product demand, and $D^{AB}(p^{AB})$ and $D^{AN}(p^{AN})$ are the aggregate world food demand for biomass and food commodity, respectively.

Equation (3) determines the equilibrium condition of biomass. The unit return of biomass, if used to produce biofuels, is given by the adjusted fuel and by-product prices net of processing costs c: $\beta r + \gamma p^O - c$. If the return from biofuel is smaller than the biomass equilibrium price in the absence of biofuel production (i.e. if $\beta r + \gamma p_o^O - c \leq p_o^{AB}$), the biofuel production is not profitable in

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[6]We assume that this coefficient also adjusts for quality differences between biofuel and fossil fuel. It therefore represents biofuel as an equivalent of fossil fuel.

[7]In order to simplify the analysis, we assumed perfect substitutability between biofuel and fossil fuel in consumption. In reality, fuel containing a low proportion of biofuels (e.g. 10% or less in the case of ethanol) can be used in virtually all standard vehicles. However, fuel with a high proportion of biofuels requires engine adaptation, which implies additional (fixed) costs to consumers. Therefore, depending on the relative importance of these adjustment costs, the theoretical model may slightly overstate the impact of biofuels on agricultural prices.

equilibrium, and the equilibrium biomass price is determined by the intersection between the biomass demand and supply on the food market, $D^{AB} = S^{AB}$ (equation 3a). In contrast, the biofuel supply is positive, $S^{B} > 0$, if the return of biomass used for the biofuel production is higher than the biomass price prevalent in the absence of biofuels: i.e. if $\beta r + \gamma p_o^O - c > p_o^{AB}$. In this case the equilibrium biomass price is determined solely by the fuel and by-product prices: $p^{AB} = \beta r + \gamma p^O - c$ (equation 3b). Equation (4) represents the equilibrium condition for food commodity by equalising farm supply and demand on the food market. The food commodity is not affected directly by biofuels because of the assumption that it is not suitable for biofuel production. However, the food commodity supply is affected indirectly through the biofuels impact on input prices, which alters the food commodity's production costs. Equations (5) and (6) determine the equilibrium on land and by-product markets, respectively. Biofuels may induce land market adjustments by affecting farm profitability and therefore alter agricultural demand for land. Equation (7) is the clearing condition for the aggregate fuel market, where $S^{TF} = S^{F} + S^{B}$ and $D^{TF} = D^{NF} + K^{AB} + K^{AN}$.

2.3 Price interdependencies

In order to understand the price transmission channels of energy, bioenergy and agricultural markets, we performed numerical simulations (see Appendix).[8] We used global agricultural, biofuel and fuel market data for 2007 to calibrate the model (see Table 1). According to the data, the share of biofuels for the total world fuel production is less than 1% using approximately 1.6% of the world's arable land area. The agricultural fuel consumption share and the biomass output share used for the biofuels is around 3.3%.

We analysed price transmission for two scenarios. First, we assumed zero biofuel production. In this case, the model is calibrated to the world agricultural and fuel data, with biofuel production set to zero ($S^B = 0$). In the second scenario we performed positive biofuel production simulations ($S^B > 0$).[9]

Price transmissions may occur in two directions: from fuel to agricultural prices and vice versa. In both directions price signals are transmitted through two channels: an indirect input channel and a direct biofuel channel. The indirect input channel affects farm production costs on the agricultural market and agricultural fuel demand has an impact on the fuel market. The direct biofuel channel interacts through biofuel demand for agricultural commodities on the agricultural market and by altering biofuel production costs on the fuel market.

2.3.1 Fuel to agriculture price transmission

To identify the price transmission from fuel to agriculture, we introduced an exogenous shock to the non-agricultural fuel demand.[10] Table 2 reports the calibrated transmission elasticities from the fuel

[8] In numerical simulations we assumed the Cobb-Douglas production function in agriculture and constant elasticity of substitution supply and demand functions.

[9] As usual, for all scenarios we performed sensitivity analyses by varying model parameters (see Appendix).

[10] In reality adjustments of both supply and demand sides in the fuel market have implications on agricultural markets. The supply side adjustments include effects such as changes in productivity and technology, changes in oil reserves, etc.

price to agricultural prices,[11] with and without biofuel production (columns 9-12) and for different model parameters values (columns 2-8).[12] The price transmission elasticities were positive for both commodities and with and without biofuel production.[13] The transmission elasticities were (more than two times) greater with biofuel production (columns 10 and 12) than without biofuel production (columns 9 and 11), because in the former case both price transmission channels were present, whereas in the latter case only the indirect input channel was present. In the absence of biofuel production, the fuel price rise is transmitted to agricultural markets by increasing agricultural production costs and by reducing commodity supplies. As a result, the prices for both agricultural commodities rose, implying positive price transmission elasticities.

With biofuel production, price transmission occurs through both the direct biofuel channel and the indirect input channel. First, as before, because of higher fuel costs, the supply of both agricultural commodities reduced (indirect input channel) causing their prices to rise. Second, the demand for biofuel pushes the prices up further (direct biofuel channel). The direct biofuel channel affected biomass and food commodity prices differently. The biomass price increased due to the direct biofuel channel because of biomass demand in biofuel production. The price for food commodity increased because the use of biomass in biofuel production increased competition for all inputs, thus pushing input prices up and causing a further upward adjustment of food commodity price. Both price transmission channels, imply a positive relationship between fuel and food prices.

Sensitivity analyses reveal that model parameters importantly impacted price transmission elasticities. A key factor affecting transmission elasticities is the relative importance of fuel input to agricultural production (α^i, for i = AB, AN). The price transmission elasticities increased in α^i (models 7 and 8 in Table 2), because agricultural production costs are more affected by fuel when it constitutes a larger share in the agricultural cost structure. Models 2 and 3 showed that the price transmission elasticities decreased food demand elasticities because a higher demand elasticity implies less agricultural price responsiveness to supply change. Note that, in a special case when food demand is perfectly elastic, agricultural commodities price would not be affected by the fuel price (not shown in Table 2). Similarly, price transmission elasticity decreases with land supply elasticity (model 6). Higher land supply elasticity implies greater land availability, allowing land to

The demand side adjustments include, among others, the economic growth and the induced change in energy requirement, changes in consumption patterns (e.g. shift to more fuel-efficient cars), etc.

[11] We calculated the elasticities by dividing the simulated percentage change of agricultural commodity price by the simulated fuel price percentage change.

[12] See the Appendix for more information about model parameter selection.

[13] The elasticities in Table 2 are in line with Hayes et al (2009). Hayes et al use a partial equilibrium FAPRI model of the world agricultural sector to examine the impact of energy prices and policies on agricultural markets. They assume high energy price scenarios with and without biofuel policies and with and without biofuel demand growth constraints. The most comparable results were the scenarios which assumed an increase in energy price and no change in policies. Based on their reported price results for 14 agricultural commodities, we have calculated the elasticities of agricultural commodities with respect to crude oil price. The elasticities varied between -0.11 to 1.27. Most commodities have elasticity greater than 0.2. Only soybean oil price had a negative elasticity (-0.11). The most elastic was corn (between 0.49 and 1.27 with and without biofuel demand growth constraints, respectively), followed by soybeans (0.22 and 0.57) and wheat (0.23 and 0.52). The least elastic were milk, cheese, beef and cotton prices (between 0.04 and 0.10).

be substituted for fuel in farm production when fuel prices rise. Finally, in models 4 and 5, price transmission elasticities without biofuels (columns 9 and 11) were almost unaffected by the non-agricultural fuel demand and fuel supply elasticities, whereas these elasticities decreased in the biofuel scenarios (columns 10 and 12).

2.3.2 Agriculture to fuel to price transmission

To analyse the price transmission from agriculture to fuel market, we assumed a positive productivity shock for both agricultural commodities.[14] The impact of rising agricultural productivity on the fuel market depends crucially on food demand elasticities, i.e. whether they are elastic or inelastic.

Food demand elasticity affects the agricultural fuel demand's market response (i.e. it affects the indirect input channel). *Inelastic food demand* causes agricultural commodity prices to greatly decrease when agricultural production increases. This implies that the productivity gain is more than offset by decreasing output prices, which ultimately reduces farm profitability, leading to lower agricultural fuel demand. The impact demand that agricultural productivity increase has on the fuel market through the indirect input channel reduced fuel prices, implying a positive transmission elasticity between agricultural and fuel prices. Second, reduced biomass prices make biofuel production profitable. Everything else equal, the direct biofuel channel has two contradictory effects on fuel prices (regardless of food demand elasticities). First, biofuels increase the fuel price, because of more agricultural demand for fuel induced by greater biomass production due to biofuel demand. Second, biofuels lower fuel price, because biofuels increase fuel supply in the energy market, exerting a downward pressure on fuel pricing.

There are similar aspects for the *elastic food demand* situation,[15] except that now higher agricultural productivity boosts the agricultural fuel demand, leading to a higher fuel price through the indirect input channel (implying a negative price transmission elasticity), while the direct biofuel channel (same as in the previous situation) may offset, weaken or strengthen the overall effect.

Table 2 (columns 13-16) reports calibrated price transmission elasticities from agriculture to fuel.[16] The transmission elasticities were relatively small (less than 0.1) because of the low share of biofuel production and agricultural fuel consumption on the aggregate fuel market (around 0.8% and 3.3%, respectively, Table 1), which scales down the agricultural sector impact on fuel prices. The elasticities were lower with biofuel production than without, in the same way as above for the fuel to agriculture price transmission. Furthermore, the results in Table 2 confirmed that the sign of the price transmission elasticities depended on the food demand elasticities (models 2 and 3). As indicated above, the price transmission elasticities may be positive or negative depending, among others, on

[14] The productivity shock affects the supply side of the agricultural market and may be due to weather effect, adoption of new technologies, etc. Similar effects may occur on the food demand side for example due to change in consumption patterns, income growth induced increase in food consumption, etc.

[15] This situation is less realistic given the fact that in general food demand tends to be price inelastic (see Appendix).

[16] The elasticities were calculated by dividing the simulated fuel price percentage change by the agricultural commodity price simulated percentage.

the demand elasticities ratio and the relative market sizes between the elastic and inelastic food demands (e.g. see columns 13 and 15 in model 2 versus model 3). Other model parameters also affected the elasticities, but had minor impact due to the low share of the biofuels and the agricultural fuel demand in the fuel market (Table 2).

These analyses imply that the food demand elasticity is an important determinant of the price transmission from agricultural to fuel markets. Overall, the indirect input channel implies a positive price transmission elasticity with inelastic food demand, and a negative elasticity with elastic food demand. Biofuels may offset, weaken or strengthen these effects.

3 Cointegration analysis

3.1 Econometric approach

The estimation of price interdependencies using time series data is subject to several issues. First, the theoretical findings from the previous section suggest that fossil energy prices affect agricultural commodity prices and, that agricultural commodity prices may affect fossil energy prices to a lesser extent. Therefore, both fossil energy and agricultural commodity prices are endogenous. In standard regression models by placing particular variables on the right hand side, the endogeneity of all variables sharply violates the exogeneity assumption of a regression equation. This problem can be circumvented by specifying a Vector Autoregressive (VAR) model on a system of variables, because no such conditional factorisation is made a priori in VAR models. Instead, variables can subsequently be tested for exogeneity, and restricted to be exogenous then. These considerations motivate our choice of the VAR model for studying the interdependencies between the energy, bioenergy and agricultural price series.

Second, given that price series are usually non-stationary, the empirical estimation of the VAR model is complicated. According to Engle and Granger (1987), if some of the series in are non-stationary, the VAR in differentiated data will be wrongly specified, which implies that non-stationary processes have to be analysed differently to stationary processes. One way to deal with non-stationarity is to difference the respective variables to remove random walk and/or trend components and then employ the Box-Jenkins method. The drawback of this approach is that valuable information about the variables' potential long-run relationship is lost. Another way to deal with non-stationarity was proposed by Engle and Granger (1987), who have shown that even if each of the variables is non-stationary, a linear combination of them might be stationary. This linear combination, which is called the cointegrating equation, may be interpreted as a long-run equilibrium relationship among the variables.

The presence/absence of cointegration determines the specification of the model to be used for causality testing. If the series are cointegrated, then causality testing should be based on a Vector Error Correction model (ECM) rather than on an unrestricted VAR model (Johansen, 1988; Johansen, and Juselius, 1990). Otherwise, if cointegration is not modelled, the evidence may vary significantly towards detecting causality between the predictor variables. Specifically, the absence of cointegration could mean the violation of the necessary condition for the simple efficiency hypothesis, which implies an absence of a long-run relationship between the oil and agricultural commodity prices. Alternatively, based on the underlying conceptual framework (section 2), a failure to find cointegration may be attributed to the non-stationarity of other components of the underlying relationship between the crude oil and agricultural commodity prices, such as the non-fuel input prices in agriculture.

The concepts of cointegration and error correction will enable us to study both the long-run relationship between the price series and the deviations from their respective long-run trends and gather a better understanding of the food, energy and bioenergy market inter-linkages. However, cointegration as such does not say anything about the causality of the series interdependencies, which however is a central question in our study. For example, one of the oil or agricultural commodities could be a price leader and the others price followers; or, alternatively, none of the commodities might be more important than the others. In the first case, the price of the leading commodity would be driving the prices of the other oil/agricultural commodities (be 'exogenous' to the other prices), and cointegration could be analysed from the equations for the other 'adjusting' prices, given the leader's price. In the second case, all prices would be 'equilibrium adjusting' and, therefore, all equations would contain information about the cointegration relationships. In order to identify the direction of causality, we performed Granger causality tests.

3.2 Data

Our data consists of weekly price observations for crude oil and nine major traded agricultural commodities: corn, wheat, rice, sugar, soybeans, cotton, banana, sorghum and tea between 1993 and 2008.[17] Crude oil prices are from the *Statistics of Norway* (1991-1996) and *Energy Information Administration* (1997-2011); agricultural output prices are from the *Food and Agriculture Organisation* (FAO).[18] Given that these prices are from markets located in major world trade centres, such as US Gulf (maize, wheat, soybeans) or Bangkok (rice), they represent the world price. All prices are border prices, i.e. free on board (f.o.b.) or cost, insurance and freight (c.i.f.) prices in US dollars (USD).

To identify the direct biofuel channel and the indirect input channel, we divided the price series into three equal sample periods: 1993-1998, 1999-2004 and 2005-2010.[19] The data split was based on the structural changes to the production, demand and policies for oil, bioenergy and agricultural commodities. In each period there are 313×10 weekly observations, 939×10 observations in total. The segmentation of the sample roughly corresponds to structural breaks. The first break accounts for the reduction in the OPEC spare capacity (defined as the difference between sustainable capacity and the current OPEC crude oil production). The effect of this event on price dynamics is evident in

[17]The weekly price data for wheat starts from 1998 and for sugar, banana and tea from 1997. Monthly sugar price data is used for this period.

[18]See the Appendix for data description and main sources.

[19]A similar approach was followed by Campiche et al. (2007).

the data, and it can be summarised in the accelerated rise of the average level of oil prices and in the increased volatility. Furthermore, the biofuel production was relatively low in the first period. The second break is related to increase in bioenergy policy support in developed economies (e.g. EU) and hence stimulating biofuel production. According to the theoretical analysis in section 2, the interdependencies between fuel prices and agricultural prices is expected to be stronger in the third period, when biofuel production expanded significantly This was driven by structural change in the world economy and energy sector leading to a sustained rise in oil prices. Therefore, one may expect that both price transmission channels are active in the third period, while in the first period only the indirect input channel is likely to be present. Usually, empirical studies analyse price interdependencies between energy and agricultural commodities over the whole available period (Yu et al., 2006), and hence they do not consider the structural breaks in the series. Second, none of the available studies test for different price transmission channels. For example, Campiche et al., (2007), who use the approach closest to ours, does not differentiate between alternative price transmission channels.

3.3 Empirical results

We started pre-testing the ten price series for stationarity and determining lag length. The stationarity was tested using the Augmented Dickey-Fuller (ADF) and Phillips Perron tests (PP). Table 3 summarises the ADF test results and Table 4 summarises the PP test results on the level and first differences. The null hypothesis is a unit root for each variable in both tests. Both ADF and PP tests fail to reject the null hypothesis of unit root suggesting that the levels of all ten prices are non-stationary (Tables 4 and 5, columns 2, 4 and 6). One way to achieve price stationarity is to differentiate/de-trend the series. Both ADF and PP unit root tests of first differences reject the null of a unit root for the ten prices (Tables 4 and 5, columns 3, 5 and 7). These results suggest that the nine agricultural commodity and crude oil prices in all three periods are integrated of order 1, i.e. they are stationary in first differences.

Based on the unit root test results we determined the lag length, n. The most common procedure is to estimate a vector autoregression using the undifferenced data, and then use the same lag length tests as in a traditional VAR. In STATA, we determined the lag length using the Schwarz Information Criterion and Akaike Information Criterion. Both information criteria suggest the optimal lag length of 1 for all three periods (a maximum of 4 lags was considered).

We then examined whether cointegrating vectors existed among the nine agricultural commodity price series and crude oil. We tested for cointegration between the world market prices for crude oil and each of the nine commodities using the likelihood ratio and trace tests, both of which determine cointegration rank, r. The trace and Max-eigenvalue, $\lambda_{\max}$, statistics obtained for the cointegration rank tests are reported in Table 5. According to Table 5, the Johansen cointegration test results suggest that there are no cointegration relationships in the first period (1993-1998). Both the trace and Max-eigenvalue, $\lambda_{\max}$, statistics of the cointegration rank tests are lower than the critical values at 10% significance already at the first instance ($r = o$).

The test results are different for the second period (1999-2004), where both the trace and the likelihood ratio tests rejected the absence of cointegration relation between crude oil and corn, and crude oil, and soybeans price series at 10% significance level, which implies that there is a cointegration relationship between crude oil and corn prices, and crude oil and soybean prices (Table 5). These results are in line with Campiche et al. (2007), who found that corn prices and soybean prices were cointegrated with crude oil prices in the 2006-2007 period. For the other seven agricultural commodities (wheat, rice, sugar, cotton, banana, sorghum and tea) both Johansen cointegration tests reject the presence of a cointegrating vector with crude oil. These results are consistent with Yu et al. (2006) findings, who examined the relationship between crude oil prices and vegetable oils for biodiesel production (soybean, sunflower, rapeseed and palm oil), and found only one cointegrating vector among the four examined vegetable oil and crude oil prices for the 1999-2005 period.

The cointegration test results are even more different for the third period (2005-2010). According to the likelihood ratio test statistics (Table 5), all nine agricultural commodity prices and crude oil prices contain a cointegrating vector. The trace test results are similar. The presence of a cointegration relationship between the crude oil and agricultural commodities prices suggest that these series tend to move towards an equilibrium relationship in the long-run. These results are in line with Hameed and Arshad (2008), who investigate the long-term relationship between petroleum and vegetable oils prices (palm, soybean, sunflower and rapeseed oil), and find a long-run equilibrium relationship between the petroleum and palm, soybean, sunflower and rapeseed oil prices.

In general, the results reported in Table 5 are perplexing. A higher significance of the price interdependencies in the third period compared to the first period indicates that there was a direct biofuel price transmission channel. Biofuel production expanded significantly in recent years, which has affected the inter-linkages between fuel and agricultural prices. These results are consistent with the theoretical results shown in Table 2, where the calibrated elasticities with biofuel production (columns 9/13 and 11/15) are higher than those without (columns 10/14 and 12/16). However, the absence of price interdependencies in the first period (1993-1998) is perplexing. In this period, when the biofuel sector was relatively small and was not likely to have affected other markets, fuel prices and agricultural prices are expected to only be interlinked through the indirect input channel. The empirical results indicate that the indirect input channel of price transmission is small and statistically insignificant. This could be due to the fact that we have analysed world agricultural prices which are also affected by production in less developed countries. These countries tend to use less fuel based inputs (e.g. machinery, fertilisers), but more labour intensive technologies. This is consistent with the underlying theoretical framework (Table 2, models 7 and 8), where price transmission elasticities decrease the relative importance of fuel used in agricultural inputs employed in agricultural production.

The fact that corn and soybean prices, which are among the key agricultural commodities used for biofuel production, are cointegrated with oil prices in the second and third period (1999-2004), while the remaining commodities are cointegrated only in the third period (2005-2010) (Table 5), may indicate a delayed price transition particularly for non-biofuel agricultural commodities. As shown in section 2, biofuels affect non-biofuel agricultural commodities through agricultural factor prices (e.g. land, labour). The expansion of biofuels induces a higher production of biofuel agricultural commodities (e.g. corn, soybeans), which in turn increase agricultural factor prices. Higher factor prices push up agricultural production costs raising the non-biofuel agricultural commodity prices. The delayed price transition may be a result of various institutional and market rigidities present in rural factor markets (e.g. land rental contracts; constrained access to capital). First, biofuel agricultural commodities respond to biofuels, and then, after adjustments in the factor markets, other commodities follow.

Finally, in order to identify a structural model and determine whether the estimated model is reasonable, we performed innovation accounting and causality tests on the error-correction model (model 9). The Granger causality tests suggest long-run unidirectional causality from oil price to agricultural commodity prices. However, the tests deny the presence of a similar relationship in the opposite direction. The coefficients of the error-correction term are highly significant, suggesting that the error-correction term acts as a significant force, which causes the integrated variables to return to their long-run relationship when they deviate from it in all the cases. Furthermore, the magnitudes of the error correction term indicate that it tends to correct the deviation at a low speed. Based on these results we cannot reject the underlying theoretical model (section 2).[20]

The impulse response analysis suggests that all agricultural commodity prices are affected by energy prices, including those that are not directly used for bioenergy production. Second, the impact of a positive oil price shock on agricultural commodities is considerably larger than vice versa. In nominal terms (changes in prices, USD), the largest long-run impact of a positive oil price shock (ca. USD 29/barrel) is on tea prices (ca. USD 50/tonne) and on cotton (ca. USD 40/tonne). In value terms, the impact is smaller on wheat, corn and rice markets (USD 8-12/tonne). The smallest response is estimated for sorghum (ca. USD 3/tonne). These results are in line with the underlying conceptual framework (section 2)[21] and previous studies (Campiche et al., 2007, Hameed and Arshad, 2008, and Yu et al., 2006). The oil price response on agricultural commodity price shocks is insignificant.

The impulse response analysis results allow us to calculate the long-run (ca. 3 years) price transmission elasticities (Table 6). Generally, the price elasticities of agricultural commodities with respect to oil (left panel) are larger than the oil price elasticities with respect to agricultural commodities (right panel). Agricultural commodities' transmission elasticity with respect to oil is

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[20]Apart from the conventional linear Granger test we applied a new nonparametric nonlinear causality testing by Diks and Panchenko (2006) after controlling for cointegration. In addition to the traditional pair-wise analysis, we tested for causality while correcting other variables' effects. The results were similar and therefore not reported.

[21]The theoretical elasticities in Table 2 show relatively high values for the causality from oil price to agricultural commodity prices (columns 9-12) and small values (close to zero) for the causality in the opposite direction (columns 13-16).

strictly positive: fuel price makes all nine agricultural commodity prices increase. The response size depends, among others, on the biofuel demand for agricultural commodities and on the relative importance of fuel in the agricultural cost input structure. Our findings suggest that price transmission elasticity is higher for those agricultural goods, which are also used for bioenergy production (sugar, soybeans, corn and wheat). According to the underlying conceptual framework, this may occur due to differences in production technologies between agricultural commodities. The magnitude of the estimated elasticities ranges between 0.04 and 0.27 and is in the same range as in Rahim et al. (2008), who estimate long-run price elasticities for rice and soybeans at 0.16 and 0.32, respectively. Our estimated elasticities, although slightly higher, are also consistent with the elasticities found in simulation studies using Computable General Equilibrium (CGE) models. For example, in the Birur et al. study (2008), elasticities vary between 0.01 and 0.11. Grains, oilseeds and sugar cane have elasticities between 0.04 and 0.11. For other agricultural commodities, elasticities range between 0.01 and 0.10. Gohin and Chantret's simulation results (2010) suggest that the elasticity for wheat is between 0.01 and 0.03.[22] The estimated elasticities (Table 6) are also in line with the theoretically predicted elasticities (Table 2) in terms of sign, but are lower in terms of magnitude. We assumed perfect market adjustments in the theoretical model. In reality, however, market rigidities and market imperfections may reduce or delay price adjustments.[23] The theoretical elasticities reported in Table 2 can be considered as an upper bound.

The estimated elasticities of oil price with respect to agricultural commodity prices are considerably smaller, and for two products (cotton and tea) are even negative (right panel in Table 6). Several reasons might be responsible for these results. First, the share of agricultural fuel consumption and biofuel production is relatively small in the total fuel consumption. Second, because the theoretical impact of agricultural prices on the fuel price is ambiguous: the causality between agricultural prices and fuel price through both direct and indirect channels of price transmission could be positive or negative (section 2).

4 Conclusions

The present paper studied the interdependencies between the energy, bioenergy and food prices. First, we developed a vertically integrated partial equilibrium market model to theoretically study the interdependencies between fuel prices and agricultural prices. In contrast to previous studies, we considered two price transmission channels: a direct biofuel channel and an indirect input channel. Among others, we showed that the impact of fuel price on agricultural prices is stronger with biofuel production than without it. Second, we applied time-series analytical mechanisms to nine major traded agricultural commodity prices, including corn, wheat, rice, sugar, soybeans, cotton, banana, sorghum and tea, along with one weighted average, world crude oil prices for the 1993-2010 period. In order to account for structural breaks, we segmented the price series into three equally sampled

[22]Note that Birur et al. (2008) and Gohin and Chantret (2010) do not report price elasticities. We have calculated the elasticities based on the reported percentage price changes for agricultural commodities and crude oil.

[23]For example, Saitone et al. (2008) show that market power in the processing sector may reduce price adjustments on agricultural markets.

periods: 1993-1998, 1999-2004 and 2005-2010. The main objective was to identify price transmissions' indirect input channel and direct biofuel channel. The interdependencies between fuel and agricultural prices are expected to be stronger in the third period biofuels expanded during this period.

Our empirical findings confirm the theoretical hypothesis that energy prices do affect prices for agricultural commodities and the interdependencies between the energy and food markets are increasing over time. Whereas we did not find any cointegration relationships in the first period (1993-1998), we found that out of nine agricultural commodity prices only corn and soybeans are cointegrated with crude oil prices in the second period (1999-2004). However, the co-integration is weaker (less present) than theoretically predicted, which indirectly indicates that the price transmission indirect input channel is small and statistically insignificant. In the third period (2005-2010) we found that the prices for all nine agricultural commodities are cointegrated with crude oil prices, indicating the presence of the direct biofuel channel. The causality tests suggest that there is a long-run Granger causality from oil to agricultural commodity prices, but not vice versa. Based on the innovation accounting results, we calculated the long-run price transmission elasticities. The impulse response analysis results suggest that all agricultural commodity prices are affected by energy prices, including those that are not directly used for bioenergy production. The impact of a positive oil price shock on agricultural commodities is considerably larger than vice versa. The magnitude of the long-run price transmission elasticities varies between 0.04 and 0.27 (or the fuel price increase by USD 1/barrel increases agricultural commodity prices between USD 0.09/tonne and USD 1.65/tonne).

Our findings are highly important for policy makers, as they explain the role of biofuels (and biofuel policies) in determining agricultural prices. According to our results, the biofuel channel is a more important driver of agricultural price changes rather than the input channel. These results suggest that policies, which stimulate biofuel production (which is the case of many developed countries), may indeed have an impact on food prices and that their impact is stronger than that of higher energy costs in agriculture. These findings contradict some recent statements made by EU and US policy executives who try to play down the role of bioenergy policy spillovers to the food and energy prices.

References

Abler, D., 2001. Elasticities of Substitution and Factor Supply Elasticities in Canadian, Mexican and United States Agriculture: A Review of Past Studies, in OECD Market Effects of Crop Support Measures. Paris, pp. 57-88.

Abo-Zaid M. S. 2010. Sticky Wages, Incomplete Pass-Through and Inflation Targeting: What is the Right Index to Target? Journal of Economics and Econometrics, 53: 28-58.

Arndt C., Benfica, R., Maximiano, N., Nucifora, A.M.D., Thurlow, J.T., 2008. Higher Fuel And Food Prices: Impacts and Responses for Mozambique. Agricultural Economics 39(1), 497-511.

Balcombe, K., Prakash, A., 2000. Estimating the Long-run Supply and Demand for Agricultural Labour in the UK. European Review of Agricultural Economics 27, 153-166.

Birur, D., Hertel, T., Tyner, W., 2008. "Impact of Biofuel Production on World Agricultural Markets: A Computable General Equilibrium Analysis," GTAP Working Paper 2413, Purdue University.

Brons, M., Nijkamp, P., Pels, E., Rietveld, P., 2006. "A Meta-analysis of the Price Elasticity of Gasoline Demand. A System of Equations Approach." Tinbergen Institute Discussion Papers 06-106/3, Tinbergen Institute.

Ciaian, P., Swinnen, J.F.M., 2009. Credit Market Imperfections and the Distribution of Policy Rents. American Journal of Agricultural Economics, 91(4), 1124-1139.

Ciaian. P. and D. Kancs, 2011. "Interdependencies in the Energy-Bioenergy-Food Price Systems: A Cointegration Analysis," EERI Research Paper Series 2009/06, Economics and Econometrics Research Institute, Brussels.

Campiche, J.L., Bryant, H.L., Richardson, J.W., Outlaw, J.L., 2007. Examining the Evolving Correspondence Between Petroleum Prices and Agricultural Commodity Prices, proceeding of the AAEA Meeting, Portland, OR, July 29-August 1, 2007.

de Crombrugghe, D., Palm, F.C., Urbain, J. P., 1997. Statistical Demand Functions for Food in the USA and the Netherlands. Journal of Applied Econometrics 12, 615-645.

de Gorter, H., Just, D.R., 2008. 'Water' in the U.S. Ethanol Tax Credit and Mandate: Implications for Rectangular Deadweight Costs and the Corn-Oil Price Relationship. Review of Agricultural Economics 30(3), 397-410.

de Gorter, H., Just, D.R., 2009. The welfare Economics of a Biofuel Tax Credit and the Interaction Effects with Price Contingent Farm Subsidies. American Journal of Agricultural Economics 91(2), 477-488.

Diks, C., Panchenko, V., 2006. A new statistic and practical guidelines for nonparametric Granger causality testing," Journal of Economic Dynamics and Control 30(9-10): 1647-1669.

Engle, R.F., Granger, C.W.J., 1987. Co-integration and error correction: representation, estimation and testing. Econometrica, (55), 251-276.

European Commission 2008. "Commission's/EU's response to the high oil and food prices." European Commission MEMO/08/421, Brussels.

FADN 2009. Farm Accountancy Data Network (FADN) data for 2009, European Commission, http://ec.europa.eu/agriculture/rica.

FAO 2008. "Growing Demand on Agriculture and Rising Prices of Commodities; An Opportunity for Smallholders in Low-Income, Agricultural-based Countries?" Proceeding of the Thirty-first session of IFAD's Governing Council, 14 February 2008.

FAOSTAT 2009. http://faostat.fao.org/

Fischer, G., 2008. Implications for Land Use Change. Proceeding of the Expert Meeting on Global Perspectives on Fuel and Food Security, Rome.

Floyd, J.E., 1965. The Effects of Farm Price Supports on the Return to Land Labour in Agriculture. Journal of Political Economy 73, 148-158.

Gardner, B., 2007. Fuel Ethanol Subsidies and Farm Price Support. Journal of Agricultural & Food Industrial Organization 5(2): Article 4.

Gohin, A., Chantret, F., 2010. The long-run impact of energy prices on world agricultural markets: The role of macro-economic linkages. Energy Policy 38(1): 333-339.

Granger, C. W. J., A. A. Weiss, 1983. Time Series Analysis of Error-Correcting Models, in Studies in Econometrics, Time Series, and Multivariate Statistics, New York: Academic Press, 255-278.

Greene, D.L., Jones, D.W., Leiby, P.N., 1995. The Outlook for U.S. Oil Dependence, ORNL-6873, Oak Ridge National Labouratory, Oak Ridge.

Hameed, A.A.A., Arshad, F.A., 2008. The impact of the petroleum prices on vegetable oil prices: evidence from cointegration test. Proceedings of the 3rd International Borneo Business Conference (IBBC), 504-514.

Hayes, D.J., Babcock, B.A., Fabiosa, J.F., Tokgoz, S., Elobeid, A., Yu, T.H., Dong, F., Hart, C.E., Chavez, E., Pan, S., Carriquiry, M., Dumortier, J., 2009. Biofuels: Potential Production Capacity, Effects on Grain and Livestock Sectors, and Implications for Food Prices and Consumers. CARD Working Paper 09-487, Iowa State University.

Hemery, C., Rizet, C., 2007. "Fuel Price Elasticity of Road Freight Transport Demand in France." COST 355 - WATCH "Changing behaviour towards a more sustainable transport system" Torino 3 October 2007.

Huntington, H.G., 1991. "Inferred Demand and Supply Elasticities from a Comparison of World Oil Models." EMF WP 11.5, The Energy Modeling Forum, Stanford University, California, January.

IEA 2006. World energy Outlook. Paris, OECD/International Energy Agency.

IEA 2009. Oil Market Report. International Energy Agency.

Imai, K., Gaiha, R., Thapa, G., 2008. Food and Oil Prices and their Implications for Rural Poverty. Mimeo.

Johansen, S., Juselius, K., 1990. Maximum likelihood estimation and inference on cointegration -- with applications to the demand for money. Oxford Bulletin of Economics and Statistics, 52, 169-210.

Johansen, S., 1988. Statistical analysis of cointegrating vectors. Journal of Economic Dynamics and Control, 12, 231-254.

Johansen, S., 1991. Estimation and Hypothesis Testing of cointegrating vectors in Gaussian Vector Autoregressive Models. Econometrica 59, 1551-80.

Krichene, N., 2002. World Crude Oil and Natural Gas: A Demand and Supply Model. Energy Economics 24(6), 557-576.

Mitchell, D., 2008. "A Note on Rising Food Prices" Policy Research Working Paper 4682, The World Bank, Wasington D.C.

OECD 2000. A Matrix Approach to Evaluating Policy: Preliminary Findings from PEM Pilot Studies of Crop Policy In the EU, the US, Canada and Mexico. OECD Directorate for Food, Agriculture and Fisheries Trade Directorate, Paris.

OECD 2009. OECD-FAO Agricultural Outlook 2009-2018. FAO-OECD.

Pindyck, R.S., 1979.The structure of World Oil Demand." Cambridge: MIT Press.

Piroli, G., Ciaian. P. and D. Kancs, 2011. "Land Use Change Impacts of Biofuels: Near-VAR Evidence from the US," EERI Research Paper Series 2011/11, Economics and Econometrics Research Institute, Brussels.

Rahim A. S., Zariyawati, M.A., Shahwahid, H.O.M., 2008. The relationship between selected Malaysian commodity prices and world crude oil prices, Working Paper, Universiti Putra Malaysia.

Ramcharran, H., 2002. Oil Production Responses to Price Changes: An Empirical Application of the Competitive Model to OPEC and Non-OPEC Countries. Energy Economics 24(2), 97-106.

Reynolds, D. B., 2002. Using Non-Time-Series to Determine Supply Elasticity: How Far do Prices Change the Hubbert Curve? OPEC Review (26) 2, 147-167.

Reuters 2008. "Bad policy, not biofuel, drive food prices: Merkel." Reuters, http://www.reuters.com/article/idUSKRA45973520080424.

RFA 2008. Feeding the Future: The Role of the U.S. Ethanol Industry in Food and Feed Production. Renewable Fuels Association, Washington, D.C.

Saitone, T.L., Sexton, R.J., and Sexton, S.E., 2008. Market Power in the Corn Sector: How Does It Affect the Impacts of the Ethanol Subsidy. Journal of Agricultural and Resource Economics 33(2), 169-194.

Salhofer, K., 2001. "Elasticities of Substitution and Factor Supply Elasticities in European Agriculture: A Review of Past Studies." In OECD Market Effects of Crop Support Measures. Paris, 89-119.

Swinnen, J. 2010. "The Right Price of Food: Reflections on the Political Economy of Policy Analysis and Communication," LICOS Discussion Paper 259, Centre for Institutions and Economic Performance, K.U.Leuven.

Thijssen, G., 1988. Estimating a Labour Supply Function of Farm Households. European Review of agricultural Economics 15, 67-78.

Tokgoz, S., 2009. "The Impact of Energy Markets on the EU Agricultural Sector." Staff General Research Papers 13024, Iowa State University, Department of Economics.

UN, 2009. UN National Accounts Main Aggregates Database, http://unstats.un.org/unsd/snaama.

Yu, T.H., Bessler, D. A., Fuller, S., 2006. Conintegration and causality analysis of world vegetable oil and crude oil prices, proceedings of the AAEA Annual meeting.

5 Appendix: Model assumptions and parameter values

The data used to calibrate the model are shown in Table 1. We used two values (upper and lower bound) for each key parameter to analyse the sensitivity of the results. We proxied the share of fuel on total farm costs with the cost share of energy in the total agricultural cost structure. The energy cost share (e.g. fuel, electricity) varies significantly across regions. There are particularly strong differences between developed and developing countries. OECD (2000) estimates that the energy cost share for the US is 0.08. Based on the calculation from the FADN (2009) the energy cost share varies between 0.04 and 0.13 in EU Member States. Energy also enters indirectly in agriculture particularly through fertilisers and pesticides. OECD (2000) estimates fertiliser and chemical cost share at 0.14 for the EU and 0.17 for the US. According to FADN (2009) the share of fertilisers and crop protection inputs varies between 0.03 and 0.14 among EU Member States. We used the parameters (α^{AB}, α^{AN}) equal to 0.15 as lower bound and 0.3 as upper bound in the model.

The most commonly used values for food demand elasticities (μ^{AB}, μ^{AN}) in the literature vary between -0.1 and -0.7 (e.g. Floyd, 1965; de Crombrugghe et al., 1997; OECD, 2000; Ciaian and Swinnen, 2009). We used the elasticity -0.5 for the lower bound. Elasticity size in terms of whether the food demand is elastic or inelastic has an important implication on the results. For this reason the upper value was set to -1.5. For the by-product demand elasticity we assume a value equal to -1.0. We did not perform sensitivity analyses with the by-product demand elasticity.

We used land supply elasticity, ε^N, of 0.2 and 1.5. In empirical studies the land supply elasticity is usually found to be rather low, mostly due to natural constraints. For example, based on an extensive literature review Salhofer (2001) concludes that a plausible range of land supply elasticity for the EU is between 0.1 and 0.4. Similarly, Abler (2001) finds a plausible range between 0.2 and 0.6 for the US, Canada and Mexico. However, the FAO (2008) reports a substantial amount of additional land - up to 2 billion hectares - potentially suitable for crop production. Fischer (2008) estimates that between 250 and 800 million hectares are potentially available for expanded crop production after excluding forest land, protected areas and land which needs to meet increased demand for food crops and livestock. We used a relatively high upper value for land supply elasticity (1.5) also because the land input is a proxy for all non-fuel inputs in our model. Supply elasticities of non-fuel and non-land inputs vary widely: between 0.1 and 3 (Balcombe and Prakash, 2000; OECD, 2000; Thijssen, 1988), because it covers a wide range of inputs (e.g. fertilisers, labour), which have various reactions to prices.

We based our assumption for non-agricultural fuel demand elasticity on the studies which estimate the demand elasticity for all sectors in the economy. Studies estimating elasticity separately for non-agricultural fuel demand are not available. The estimated values lie between -2.0 to 0.3, but most studies place the this number between -1.0 and 0.0 (e.g. Brons et al., 2006; Hemery and Rizet, 2007; Krichene, 2002; Greene et al., 1995; Pindyck, 1979). We used non-agricultural fuel demand elasticity, μ^{NF}, in the model equal to -0.5 and -1.5.

The estimates of the fossil fuel supply elasticity vary in the literature between -0.40 and 1.0 (Krichene, 2002; Greene et al., 1995; Ramcharran, 2002; Reynolds, 2002). There is evidence that OPEC countries have negative elasticity explained by the target revenue hypothesis accompanying the backward-bending supply curve, while non-OPEC countries show positive supply elasticity (Ramcharran, 2002). In general, the short-run elasticities of fossil fuel demand and supply are very small in comparison to their long-run elasticity. The long-run fuel market elasticities are about ten times greater than short-run elasticities (Huntington, 1991; 1994; Greene et al., 1995; Krichene, 2002). We used fossil fuel supply elasticity, ε^F, equal to 0.3 as lower bound and 1.00 as upper bound.

Table 1: Data description and sources

Variable	Value	Unit	Coverage	Year	Source
Agricultural area	1411	million ha	World	2007	FAOSTAT[1]
Land used for biomass crops	684	million ha	World	2004	FAOSTAT[2]
Land used for biofuels	23	million ha	World	2007	IEA (2006), OECD (2009)
Land used for food commodity	1046	million ha	World	2007	Calculated[3]
Total agricultural production	2030	Billion USD	World	2007	UN (2009)[4]
Biomass production	983	Billion USD	World	2007	Calculated[5]
Biomass production in food use	951	Billion USD	World	2007	Calculated[6]
Biomass production in biofuel use	33	Billion USD	World	2007	Calculated[7]
Food commodity production	1046	Billion USD	World	2007	Calculated[8]
By-product commodity production	10	Billion USD	World	2007	Calculated[9]
Fossil fuel supply	30390	Million barrels	World	2007	IEA (2009)[10]
Biofuel production	257	Oil equivalent	World	2007	FAO (2008)[11]
Agricultural fuel demand	1053	Million barrels	World	2007	Calculated[12]
Non-agricultural fuel demand	30594	Million barrels	World	2007	Calculated[13]
Biofuel extraction coefficient	7.8	Ratio	World	2007	Calculated[14]
By-product extraction coefficient	17/56=0.30	Ratio	US	-	RFA (2008)[15]

Notes: [1]Agricultural area is proxied with the world arable area; [2]Total area of main biofuel crops; [3]Total agricultural area minus land used for biomass; [4]Proxied by the estimated value added of agriculture, hunting, forestry, fishing; [5]The share of land used for biomass crops multiplied by the total agricultural production; [6]The share of land used for biomass for food multiplied by the biomass production; [7]The share of land used for biofuels multiplied by the biomass production; [8]The share of land used for food commodity multiplied by the total agricultural production; [9]By-product extraction coefficient (0.3) multiplied by the biomass production used for biofuels; [10]Proxied with the total world oil demand by multiplying the world oil demand of 86 million barrels per day in 2007 by 365; [11]The value was obtained by multiplying world biofuel production in 2007 (36.12 Mtoe) with the barrel conversion factor (7.11); [12]The share of the estimated value added of agriculture, hunting, forestry, fishing on total value added multiplied with total fuel; [13]The share of the estimated value added of the rest of the economy on total value added multiplied with total fuel; [14]Biofuel production multiplied by biomass production used for biofuels; [15]According to RFA (2008) each 56-pound bushel of corn processed by a dry mill results in approximately 17 pounds of distillers grains and 2.8 gallons of fuel ethanol.

Table 2: Calibrated price transmission elasticities

Model	Model assumptions (Parameters from the literature)							Calibrated elasticities, fuel price → agricultural prices				Calibrated elasticities, agricultural prices → fuel price			
								Fuel → biomass		Fuel → food		Biomass → fuel		Food → fuel	
	μ^{AB}	μ^{AN}	μ^{NF}	ε^{F}	ε^{N}	α^{AB}	α^{AN}	$S^{B}=0$	$S^{B}>0$	$S^{B}=0$	$S^{B}>0$	$S^{B}=0$	$S^{B}>0$	$S^{B}=0$	$S^{B}>0$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)
1	-0.5	-0.5	-0.5	0.3	0.2	0.3	0.3	0.41	1.29	0.41	1.29	0.02	0.05	0.02	0.05
2	**-1.5**	-0.5	-0.5	0.3	0.2	0.3	0.3	0.29	1.02	0.29	1.02	0.00	0.04	0.00	0.04
3	-0.5	**-1.5**	-0.5	0.3	0.2	0.3	0.3	0.29	1.00	0.29	1.00	-0.001	0.03	-0.001	0.03
4	-0.5	-0.5	**-1.5**	0.3	0.2	0.3	0.3	0.42	0.83	0.42	0.83	0.01	0.03	0.01	0.03
5	-0.5	-0.5	-0.5	**1**	0.2	0.3	0.3	0.42	0.90	0.42	0.90	0.01	0.03	0.01	0.03
6	-0.5	-0.5	-0.5	0.3	**1.5**	0.3	0.3	0.34	0.77	0.34	0.77	0.02	0.05	0.02	0.05
7	-0.5	-0.5	-0.5	0.3	0.2	**0.15**	0.3	0.25	0.93	0.38	0.94	0.02	0.06	0.02	0.06
8	-0.5	-0.5	-0.5	0.3	0.2	0.3	**0.15**	0.38	0.85	0.25	0.82	0.02	0.06	0.02	0.06

Notes: μ^{AB} - biomass demand elasticity; μ^{AN} - food demand elasticity, μ^{NF} - non-agricultural fuel demand elasticity, ε^{F} - fossil fuel supply elasticity, ε^{N} - land supply elasticity, α^{AB} - fuel elasticity in biomass production function, α^{AN} - fuel elasticity in food production function, S^{B} - biofuel production. Further model assumptions: share of biofuel production in total fuel production = 0.8%; share of agricultural fuel demand in total fuel demand = 3.3%; share of biomass used for biofuels in total biomass production = 3.3%; share of land used for biomass production in total land use = 48.5%; share of land used for biofuels in agricultural land use = 1.6%. See Appendix for literature sources of model parameters.

Table 3: ADF unit root test results for prices of crude oil and agricultural commodities

	1993-1998		1999-2004		2005-2010	
Prices	Level	FD	Level	FD	Level	FD
Corn	-2.42	-8.92***	-2.19	-8.87***	-2.97	-8.85***
Wheat	-1.88	-10.44***	-2.35	-9.33***	-2.14	-8.99***
Rice	-1.86	-10.50***	-2.89	-10.51***	-2.20	-10.42***
Sugar	-1.48	-9.72***	-2.31	-10.90***	-2.29	-8.96***
Soybeans	-2.93	-9.34***	-2.53	-10.87***	-2.38	-9.81***
Cotton	-1.56	-9.86***	-2.87	-9.52***	-2.58	-8.93***
Banana	-1.48	-9.42***	-1.53	-10.00***	-2.68	-9.66***
Sorghum	-2.12	-10.78***	-2.40	-10.30***	-1.58	-10.97***
Tea	-1.85	-10.24***	-2.15	-9.85***	-2.44	-9.86***
Crude oil	-2.93	-13.67***	-2.60	-11.46***	-2.47	-14.53***

Notes: Augmented Dickey-Fuller test results, *** significant at 1% level. Critical Values: -4.00 (1%), -3.43 (5%), -3.14 (10%). FD: First Differences.

Table 4: PP unit root test results for prices of crude oil and agricultural commodities

	1993-1998		1999-2004		2005-2010	
Prices	Level	FD	Level	FD	Level	FD
Corn	-2.66	-10.19***	-2.15	-9.46***	-2.11	-10.25***
Wheat	-2.15	-9.41***	-1.69	-10.56***	-2.75	-9.44***
Rice	-3.02	-9.42***	-2.40	-8.85***	-2.08	-9.36***
Sugar	-1.72	-9.63***	-1.86	-9.86***	-2.88	-10.66***
Soybeans	-2.04	-9.66***	-2.90	-10.77***	-2.78	-9.46***
Cotton	-2.06	-10.45***	-2.71	-9.40***	-2.25	-9.79***
Banana	-2.24	-8.75***	-1.85	-9.74***	-1.49	-8.79***
Sorghum	-2.06	-10.13***	-2.37	-10.03***	-2.50	-10.80***
Tea	-1.54	-9.24***	-2.56	-10.67***	-2.19	-10.31***
Crude oil	-2.73	-15.44***	-1.76	-11.26***	-1.48	-11.43***

Notes: Phillips Perron test results, ***significant at 1% level. Critical Values: -4.10 (1%), -3.43 (5%), -3.17 (10%). FD: First Differences.

Table 5: Johansen cointegration test results for crude oil and food prices

	1993 - 1998				1999 - 2004				2005 - 2010			
	L-max Test		Trace Test		L-max Test		Trace Test		L-max Test		Trace Test	
	H_0: r=0	H_0: r=1	H_0: r=0	H_0: r=1	H_0: r=0	H_0: r=1	H_0: r=0	H_0: r=1	H_0: r=0	H_0: r=1	H_0: r=0	H_0: r=1
Corn - crude oil	5.71*	1.50	8.13*	1.74	12.02	2.38*	13.92	2.11*	14.12	1.21*	14.12	1.09*
	(0.021)	(0.008)	(0.022)	(0.016)	(0.109)	(0.017)	(0.072)	(0.006)	(0.067)	(0.003)	(0.061)	(0.006)
Wheat - crude oil	5.66*	2.46	6.38*	2.20	6.31*	1.53	7.49*	2.00	15.69	1.04*	15.27	1.60*
	(0.024)	(0.006)	(0.046)	(0.006)	(0.022)	(0.007)	(0.031)	(0.013)	(0.041)	(0.012)	(0.083)	(0.005)
Rice - crude oil	5.50*	1.67	5.85*	2.56	6.01*	1.54	6.39*	1.42	12.27	1.01*	14.14	1.20*
	(0.021)	(0.008)	(0.015)	(0.016)	(0.037)	(0.009)	(0.042)	(0.022)	(0.034)	(0.005)	(0.168)	(0.006)
Sugar - crude oil	6.30*	1.99	7.43*	1.52	6.04*	1.98	6.07*	1.93	15.47	1.46*	14.56	1.40*
	(0.056)	(0.005)	(0.029)	(0.008)	(0.015)	(0.007)	(0.106)	(0.008)	(0.171)	(0.005)	(0.072)	(0.020)
Soybeans - crude oil	5.22*	2.75	7.91*	2.37	12.76	2.05*	13.76	2.29*	14.50	1.64*	15.67	1.23*
	(0.015)	(0.007)	(0.060)	(0.028)	(0.239)	(0.005)	(0.054)	(0.007)	(0.162)	(0.004)	(0.076)	(0.004)
Cotton - crude oil	6.73*	2.76	6.38*	2.65	6.43*	1.87	7.95*	2.37	11.98	1.11*	13.34	1.22*
	(0.020)	(0.009)	(0.028)	(0.010)	(0.020)	(0.007)	(0.029)	(0.006)	(0.083)	(0.004)	(0.035)	(0.004)
Banana - crude oil	5.71*	2.16	7.26*	2.23	5.81*	1.42	6.80*	1.42	11.89	1.56*	13.78	1.86*
	(0.104)	(0.016)	(0.029)	(0.005)	(0.044)	(0.004)	(0.031)	(0.015)	(0.034)	(0.023)	(0.247)	(0.020)
Sorghum - crude oil	7.18*	2.17	6.79*	1.42	6.85*	2.14	5.98*	2.28	12.25	1.76*	14.05	1.34*
	(0.034)	(0.007)	(0.030)	(0.008)	(0.017)	(0.027)	(0.044)	(0.024)	(0.034)	(0.031)	(0.048)	(0.004)
Tea - crude oil	7.14*	2.39	8.22*	2.52	6.33*	1.49	6.76*	1.65	12.85	1.67*	13.37	1.02*
	(0.020)	(0.045)	(0.022)	(0.025)	(0.023)	(0.006)	(0.134)	(0.006)	(0.201)	(0.009)	(0.096)	(0.008)

Notes: Johansen (1988, 1991) L-max and Trace test statistics. r=0 - no cointegration relationship; r=1 - at most one cointegration relationship. Critical values at 10% significance level are 10.60 (r=0) and 2.71 (r=1) for the L-max test and 13.31 (r=0) and 2.71 (r=1) for the Trace test. Asymptotic significance level (p-values) in parenthesis. *denotes failure to reject the hypothesis at the 10% level.

Table 6: Estimated long-run price transmission elasticities

	Average price, USD	Agricultural commodities with respect to oil				Oil with respect to agricultural commodities			
		Impulse, USD	Response, USD	Unit response, USD	Elasticity	Impulse, USD	Response, USD	Unit response, USD	Elasticity
Oil	56.110	29.793							
Corn	142.057		10.562	0.355	0.140	43.767	0.945	0.022	0.055
Wheat	176.928		12.483	0.419	0.133	62.054	1.007	0.016	0.051
Rice	353.221		8.173	0.274	0.044	155.865	1.963	0.013	0.079
Sugar	237.291		33.429	1.122	0.265	77.598	0.068	0.001	0.004
Soybeans	304.748		26.749	0.898	0.165	95.418	0.941	0.010	0.054
Cotton	1269.489		40.657	1.365	0.060	251.643	-0.204	-0.001	-0.018
Banana	652.136		13.873	0.466	0.040	187.752	0.121	0.001	0.007
Sorghum	147.288		2.857	0.096	0.037	40.823	1.011	0.025	0.065
Tea	1963.107		49.133	1.649	0.047	338.290	-0.006	0.000	-0.001

Notes: Left panel - Impulse: Positive shock in oil price (one standard deviation) in USD/barrel; response: changes in agricultural commodity prices in USD/tonne. Right panel - Impulse: Positive shock in agricultural prices (one standard deviation) in USD/tonne; response: changes in oil prices in USD/ barrel. Impulse in week 0, response in week 150.